A Hyperspectral Tethered Spectral Radiometer Buoy: Ocean Color Algorithm Development in Estuaries, Coastal Waters, and Marginal Seas

Collin S. Roesler
Department of Marine Sciences, The University of Connecticut
1084 Shennecossett Rd., Groton, CT 06340-6097
phone: (860) 405-9166 fax: (860) 405-9153 email: roesler@uconnvm.uconn.edu
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LONG TERM GOAL

The goal for this project was to upgrade a multispectral tethered spectral radiometer buoy to a hyperspectral version that would have the capability to resolved fine scale features in reflectance related to pigment absorption peaks. The scientific goals that will follow the upgrade are to test an existing hyperspectral algorithm to extract the contributions to reflectance due to absorption and backscattering by particulate and dissolved components in optically deep waters (Roesler and Perry, 1995) and in optically shallow waters (Werdell and Roesler, in prep.).

SCIENTIFIC OBJECTIVES

The specific projects include: (1) the modification of an algorithm to estimate the spectral absorption coefficients by water, phytoplankton, tripton and gelbstoff and the spectral backscattering coefficients by water and particles from remote sensing reflectance; (2) modification and testing of a reflectance model to estimate the composition of the benthic substrate and further to predict the health of biologically dominated substrates; (4) identification and quantification of harmful algal species in the presence of other optically active material and non-toxic phytoplankton species.

APPROACH

This grant was used upgrade an existing multispectral TSRB in to a hyperspectral model. The moneys from this grant stimulated the development of that hyperspectral instrument by Satlantic, Inc. While the instrument was not delivered until late October 1998, program development was maintained using the multispectral TSRB and by modifying and testing the algorithms on the multispectral data or on published data.

WORK COMPLETED

Algorithm modification for Remote Sensing Reflectance over optically deep waters

An existing model (Roesler and Perry 1995) which was developed to extract component absorption and backscattering properties from in-water hyperspectral *irradiance* reflectance in clear ocean waters has been modified for application to multispectral to hyperspectral resolution measurements of *radiance* reflectance in turbid waters. The modifications were tested on multispectral and hyperspectral radiance reflectance measurements made in Friday Harbor Washington as part of the ONR-sponsored Ocean Optics course. Additional tests were made with radiance reflectance spectra simulated with Hydrolight under a range of optical conditions.

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Shallow water benthic substrate identification

An existing forward model of spectral reflectance over optically shallow bottoms (Maritorena et al. 1994) was modified and an inverse model was developed to extract the spectral reflectance signature of an optically shallow bottom from measurements of reflectance measured at the surface. As part of the modification, the sensitivity of the model to the assumption of Lambertian reflection by the benthos was assessed and the actual bidirectional reflectance was determined for mineralic sands and eel grass meadows (Werdell and Roesler, in prep.). A second model was developed to quantify the contributions of seagrasses, seaweeds and sediments to the inversely modeled benthic reflectance signature. These models were tested against multispectral reflectance measured with a TSRB in clear Bahamian waters overlying carbonate sand and turtle grass and in turbid Long Island Sound waters overlying mineralic sands and clays, eel grass and kelp. A paper on these results is in preparation from the Masters Thesis (Werdell and Roesler, in prep.)

Identification and Quantification of Harmful Algal Blooms

The reflectance model, as modified above, has been used to estimate the absorption spectra associated with the optically active components and the particulate backscattering spectra. Particle size distributions and IOPs of a range of harmful algal species were measured in the laboratory and the optical efficiency factors were calculated using the Mie code of Bohren and Huffman. Unique combinations of absorption and backscattering were identified for each of these species for comparison with those extracted from the reflectance measurements. As hyperspectral reflectance measurements have yet to be made with the upgraded TSRB, any existing spectra that could be found in the literature were used to test the model in order to identify the algal group associated with the observed red tide. Two manuscripts have been prepared from these results and have been submitted to SPIE for presentation in the fall meeting (McLeroy-Etheridge and Roesler, and Roesler and McLeroy-Etheridge). In addition, a invited presentation on the influence of harmful algal blooms on ocean color with be given at the 1999 Ocean Sciences Meeting in Santa Fe, NM in February.

RESULTS

Shallow water benthic substrate identification

Multispectral radiance reflectance transects were measured over substrates that varied in depth and in composition from sand to seagrasses in clear Bahamian waters and turbid Long Island Sound waters (Figures 1a and 2a). The contribution of benthic reflectance to the measured surface reflectance was estimated from the inverse model (Figure 1b and 2b). The second model was used to estimate the relative contributions by the sand and seagrasses (Figure 1c and 2c). While the depth along the transect varied (Figures 1d and 2d), it is apparent that the inverse model was able to separate the change in surface reflectance due to an increasing water depth from that due to a change in the reflectance of the benthic substrate. In the case of the Bahamian waters, the surface reflectance was decreasing suggesting that either the water was getting deeper or the bottom what getting less reflective. The latter was the case and the model correctly identified a change in substrate from pure sand to a meadow of turtle grass in sand. Although the turtle grass approached 60% coverage, the extremely bright reflectance of carbonate sand resulted in an extremely high derived total benthic reflectance. If only the magnitude of the reflectance was available, the contribution by turtle grass would likely be underestimated. However, the second model accurately extracts the contributions by sand and turtle grass based upon their unique *spectral* signatures.

In the turbid Long Island Sound waters, the low surface reflectance was observed to increase by approximately 50% midway through the transect. The derived benthic reflectance signature yielded a more dramatic change than was observed in the surface reflectance. Because these waters are so turbid and the TSRB was only equipped with SeaWiFS wavelengths, only once channel could be used, the attenuation of the other wavelengths by the water column was too extreme. However, with only one channel of derived benthic reflectance signal, the change from an eel grass meadow to bare mineralic sand was apparent. This signal was also sufficient to discern an increase in reflectance of the sand from approximately 10% to 20% as a function of distance from the meadow. This was correlated with a change in the organic coating of the sediment which has been identified as the major source of variability in temperate sand reflectivity.

Identification and Quantification of Harmful Algal Blooms

In the recently submitted papers of Roesler and McLeroy-Etheridge, the remotely sensed reflectance of three red tides comprised of different species of toxic algae were taken from the literature: blooms of *Ptychodiscus brevis* (a.k.a. *Gymnodinium breve*) along the west coast of Florida (Carder and Steward, 1985), *Gonyaulax digitale* in Bedford Basin (Cullen et al., 1997), and *Gymnodinium nelsoni* (a.k.a. *G. splendens*) in a brackish creek in the upper waters of the Chesapeake Bay (Clark and Kiefer, 1990). Reflectance spectra were measured on a helicopter, with a tethered spectral radiometer buoy, and 10 cm below the surface with a hand-held radiometer, respectively.

The inverse model of Roesler and Perry (1995) was used to determine the contributions to absorption by phytoplankton and colored dissolved and particulate organic material (CDOM and CPOM) and the contributions to backscattering by particulate material. The model, hereafter referred to as the inverse model, has been modified from that published in 1995 as follows: the capability for application to multispectral reflectance data, the inclusion of the backscattering term in the denominator for cases where the assumption $b_b << a$ does not hold, and the separation of the contributions by CDOM and CPOM.

As an example, reflectance spectra of a red tide bloom of *Ptychodiscus breve* were measured along the west Florida shelf in 1983 (Carder and Steward, 1985). Variations in the color from black to red to bright rust were observed along the transect at stations 45, 43, and 39, respectively. The associated reflectance spectra are shown in Fig. 3a. Using independent endmember absorption and backscattering spectra (Fig 3b and c), the inverse model was used to estimate the contribution of the absorbing and backscattering components. Model estimates of reflectance compared well with measured spectra (Fig. 3a) although distinct features in the residual spectra were observed in each case (Fig. 3d). With the exception of the chlorophyll fluorescence signature at 683 nm, the remaining features in the residual spectra are suggestive of pigment absorption spectra, indicating that the standard phytoplankton absorption endmember does not adequately describe the in situ phytoplankton absorption. By including the residuals in the estimate of the phytoplankton absorption component, variations in spectral shape are estimated (Fig 3e). These absorption spectra indicate that concentrations of the toxic algae were approximately 65, 35, and 5 μg chl l^{-1} at stations 39, 45, and 43, respectively, which compare well with the measured values of 63, 32 and 8 μg chl l^{-1}. In addition, the absorption spectra indicate strong pigment packaging and significant contributions by chlorophyll c and peridinin.

Estimated absorption by the tripton component (Fig. 3f) indicates that there was essentially no CPOM at station 45 and thus the estimated particle backscattering coefficient (Fig. 3g) was due entirely to the toxic algae. Assuming that the backscattering to absorption ratio was essentially constant for the algal population along the coast, the estimated particle backscattering spectra were deconvolved into contributions by the algae and contributions by CPOM (Fig. 3h and i).The shape of these backscattering spectra indicate an increase in the modal particle size of the CPOM from station 43 to 39 which resulted in a brightening of the water in spite of a factor of ten increase in phytoplankton absorption.

IMPACT/APPLICATION

The use of hyperspectral radiometer buoys, in combination with the models described here, to determine the composition of benthic substrates in shallow waters has important implications with respect to state policy on coastal land protection and coastal land use. For example, the coastal water policies of the state of Connecticut are primarily concerned with those locations in which the water depth is less than 6 m. At this point there is no method to discern the substrate of that coastal region. The ability to identify, quantify, and monitor eel grass meadows, kelp forests, and zones of high sediment transport would significantly improve the state's effectiveness with regards to point source and non-point source pollution, aquaculture permits, dredging, etc. Additionally, these approaches to estimating bottom coverage and substrate identification can be used in the refinement of methods for the identification of anthropogenic objects on the sea floor such as mines and mine-like objects.

The application of hyperspectral radiometry with the TSRB to identification and quantification of harmful algal blooms will lead to improvements in the understanding of the formation, development and persistence of these devastating blooms. There is growing evidence that many harmful blooms develop offshore and that advective processes are responsible for their occurrence in nearshore waters (Franks and Anderson, 1992; Franks 1997). Selective placement of radiometer buoys in offshore waters, in combination with the models described here, could be used to develop an early warning system for harmful blooms that may advect shoreward.

TRANSITIONS

Trevor Probyn and Stewart Bernard of the University of Cape Town, South Africa are utilizing the reflectance model (Roesler and Perry, 1995) as modified here to estimate phytoplankton absorption spectra from SeaWiFS data. In particular they are interested in discerning toxic algal blooms in the Benguelan upwelling system.

RELATED PROJECTS

1. This work overlaps significantly with my NASA-funded ECOHAB project. While the goal of this project is to gain understanding as to why the toxicity of the dinoflagellate *Alexandrium tamarense* decreases significantly in Long Island Sound compared to the Gulf of Maine, a large portion of the effort is in the development of remote sensing models to assess the occurrence of red tide blooms.

2. As part of the ECOHAB program, I lent my hyperspectral TSRB to Dr. Alan Weidemann (NRL Stennis) for use on the ECOHAB cruise off South Florida this month. I will make use of the data collected to test the remote sensing model.

3. I will be participating on a cruise with Trevor Probyn and Stewart Bernard of the University of Cape Town, South Africa, to measure inherent and apparent optical properties of red tide blooms during the upwelling season in the Benguelan Current in 2000.

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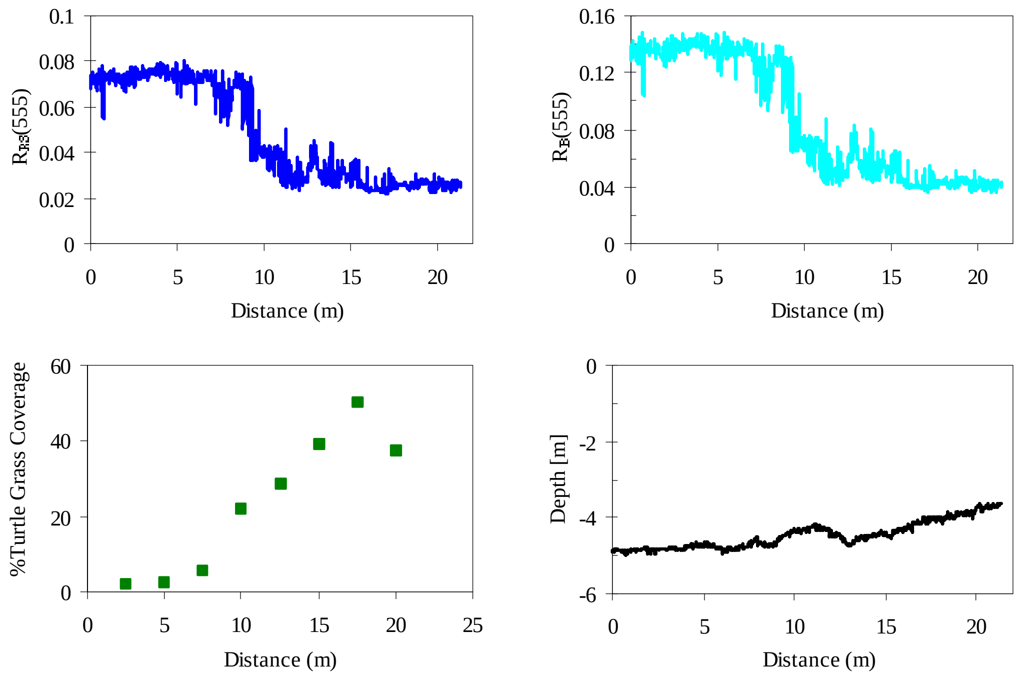

Figure 1. a. Remote sensing reflectance measured at 555 nm with a TSRB along a 20 m transect in Bahamian waters. b. Extracted benthic reflectance signature at 555 nm derived from inverse model. c. Estimated percent coverage of turtle grass along transect derived from linear least squares regression of endmember reflectance spectra measured in the laboratory against the benthic spectral reflectance signature derived from the inverse model. d. Depth along transect demonstrating how the model can distinguish between a dark substrate versus an increase in depth.

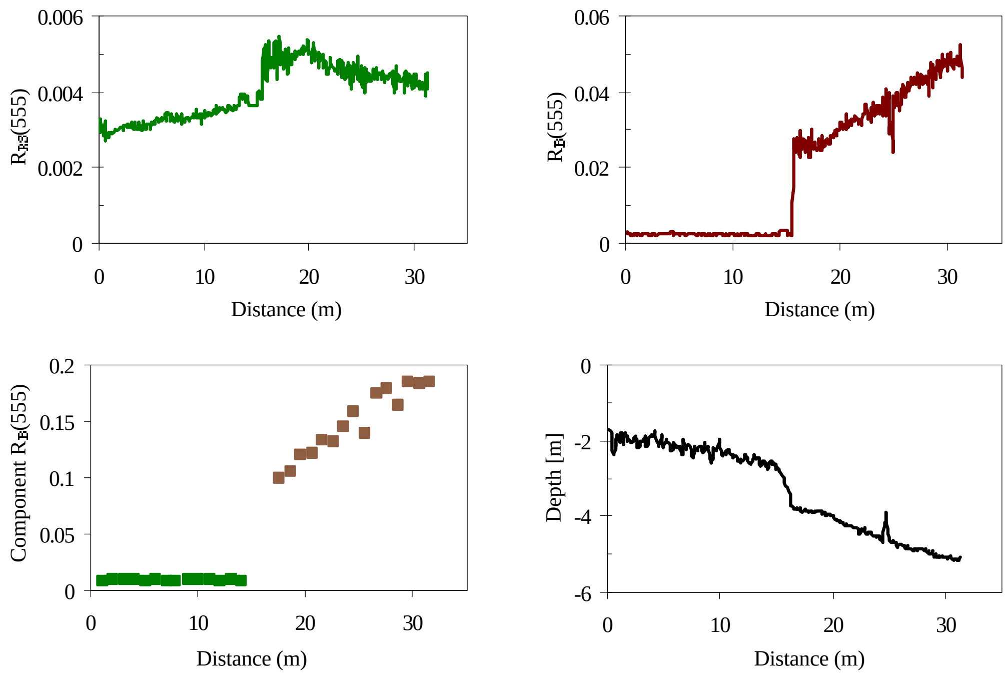

Figure 2. a. Remote sensing reflectance measured at 555 nm with a TSRB along a 20 m transect in turbid Long Island Sound waters. b. Extracted benthic reflectance signature at 555 nm derived from inverse model. c. Estimated component reflectance spectra, green indicates eel grass, brown indicates sediments which are increasing in reflectance due to decreasing organic coating with distance from eel grass meadow. d. Depth along transect demonstrating how the model can recognize increasingly reflective sands in presence of increasing bottom depth.

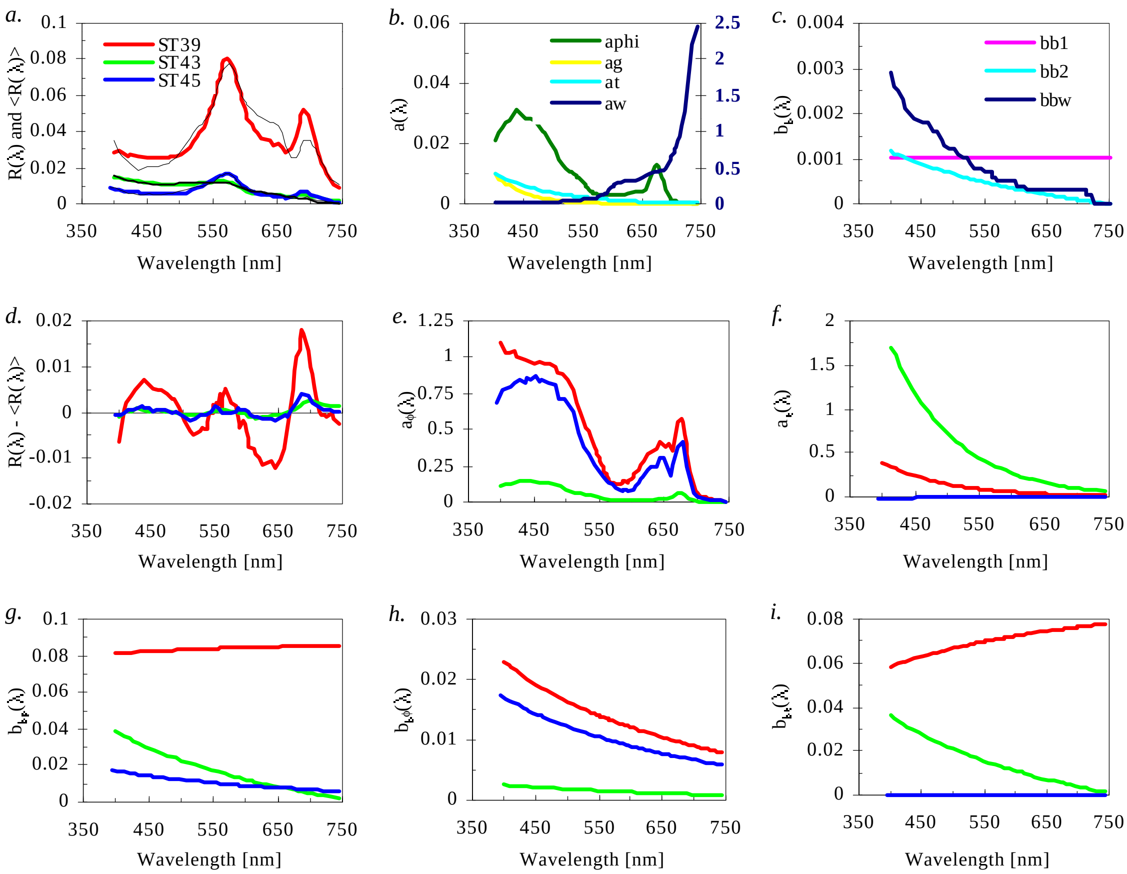

Figure 3. Results of the inverse model of Roesler and Perry (1995) applied to remotely sensed reflectance measured from a helicopter over a Ptychodiscus breve bloom along the west Florida shelf (Carder and Steward, 1985). a. Measured (bold colored lines) and modeled (thin black lines) reflectance spectra for three stations over the red tide bloom. Non-dimensional absorption (b) and backscattering (c) basis vectors for the model. d. Model residuals for the three stations. Positive values indicate spectral bands where input basis vector included too much pigment absorption, negative values for insufficient pigment absorption. The positive peak at 683 nm indicates the presence of natural fluorescence in the measured spectrum that was not included in the modeled spectrum. Estimated phytoplankton (e) and tripton (f) absorption spectra, residual was included in phytoplankton component. Estimated total particulate backscattering (f), and backscattering contributions by phytoplankton (h) and tripton (I).